



Statistical interpretation of the spatial distribution of current 130 GeV γ -ray line signal within the dark matter annihilation scenario

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ABSTRACT

Recently, several groups identified a tentative γ -ray line signal with energy ~ 130 GeV in the central Galaxy from the Fermi-LAT data. Such a γ -ray line can be interpreted as the signal of dark matter annihilation. However, the offset ~ 220 pc (1.5°) of the center of the most prominent signal region from the Galactic center Sgr A* has been thought to challenge the dark matter annihilation interpretation. Considering the fact that such a 130 GeV γ -ray line signal consists of only ~ 14 photons, we suggest that the “imperfect” consistency of these photons with the expected dark matter distribution is due to the limited statistics. The offset will be smaller as more signal photons have been collected in the near future. Our Monte Carlo simulation supports the above speculation.

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High energy γ -ray line is of extreme interest in search for the signal of dark matter (DM) annihilation or decay. Recently, via analyzing the publicly available Fermi-LAT γ -ray data, Bringmann et al. [1] and Weniger [2] found weak evidence for a monochromatic γ -ray line with energy ~ 130 GeV. Later independent analyses carried out by a few groups confirmed the existence of the 130 GeV γ -ray excess, and the signal has been found to be even more prominent [3–5]. This result can be interpreted by ~ 130 GeV DM annihilation, with annihilation cross section $\langle\sigma v\rangle_{\chi\chi\rightarrow\gamma\gamma} \sim 10^{-27} \text{ cm}^3 \text{ s}^{-1}$, and a cuspy density profile such as Navarro–Frenk–White (NFW, [6]) and Einasto [7].

Much attention was paid on this line signal in the community. Many models were proposed to explain this line structure, either by DM [8] or astrophysical sources [9,10]. It was also suggested to constrain the DM scenarios with the continuum γ -rays or antiprotons [11], or to test the line postulation with high energy resolution detectors [12]. Moreover, the spectra of the sum of cosmic ray electrons and positrons detected by ATIC and PAMELA both showed small wiggle-like structures at ~ 100 GeV [13,14], which could be the result of the annihilation of ~ 140 GeV DM particles into electrons/positrons, in accordance with the 130 GeV γ -ray line [15].

Among current relevant data analysis works, the morphology of the potential line signal is still in debate [3–5]. It is very attractive that Su and Finkbeiner identified that the signal

region lies basically in the Galactic center region, and the detection significance is quite high (exceeds 5σ) [5]. The former character is just expected in the DM scenario, while a confidence level $> 5\sigma$, if confirmed, is encouraging to approach a discovery/detection. The problem is however that the signal region has a center deviating from the Galactic center (Sgr A*) considerably by a distance ~ 220 pc (or angle $\sim 1.5^\circ$).¹ The result seems to be at odds with the DM models in which the signal region is expected to be centered at $(\ell, b) = (0^\circ, 0^\circ)$, where (ℓ, b) are the Galactic longitude and latitude, respectively. Indeed, such a puzzle has been thought to be one of the strongest arguments against the DM origin of the γ -ray line signal [10,16]. In this Letter, considering the fact that the current 130 GeV γ -ray line signal consists of only ~ 14 photons, we try to provide a statistical interpretation of the spatial distribution.

For such a purpose we carry out the Monte Carlo simulation of the arrival direction of the photons produced by the annihilation of DM particles. Following [5] we adopt the Einasto DM density profile in this work [7]

$$\rho(r) = \rho_s \exp\left(-\frac{2}{\alpha} \left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]\right), \quad (1)$$

where $\alpha = 0.17$, $r_s \approx 20$ kpc and $\rho_s \approx 0.06 \text{ GeV cm}^{-3}$.

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¹ For the signal region with highest significance ($\sim 4.5\sigma$, i.e., their central region) identified in [3], an offset $\sim 1.2^\circ$ was reported, too.

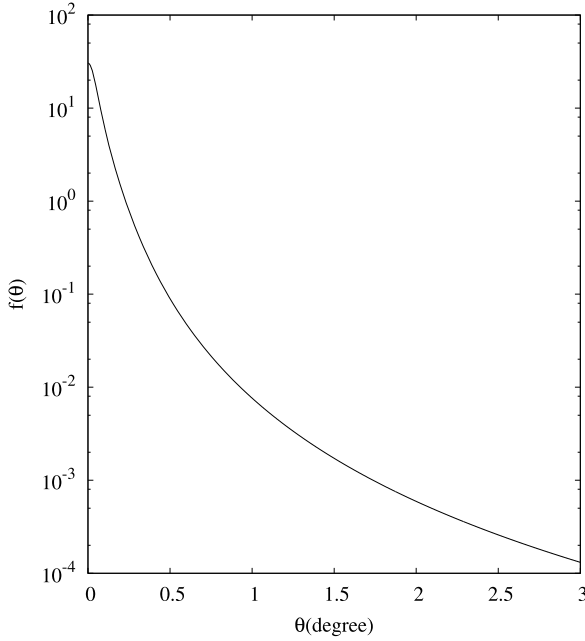


Fig. 1. The inclination angle averaged point-spread function of Fermi-LAT at 130 GeV.

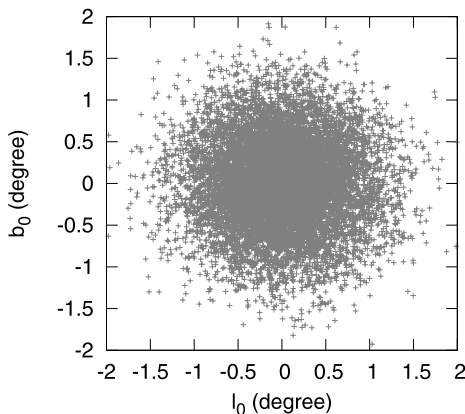
The possibility of detecting one photon at the location (ℓ, b) is proportional to the J -factor

$$J \propto \int ds \rho^2(r(s)), \quad (2)$$

where $r = (s^2 + r_\odot^2 - 2sr_\odot \cos \ell \cos b)^{1/2}$ is the Galactocentric distance, $r_\odot \simeq 8.5$ kpc is the distance from the Sun to the Galactic center and s is the line of sight distance.

In reality the “observed” (reconstructed) direction of the photons will deviate from the “real” location, and the deviation is a function of an incident photon’s energy and inclination angle. Such an effect is known as the point-spread function (PSF) of the instrument. For Fermi-LAT, the PSF function can be found on the website.² In this work, we fix the photon energy to be 130 GeV and average the PSF in different inclination angles. The derived PSF function $f(\theta)$ is shown in Fig. 1, where the normalization

² http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_PSF.html.



$2\pi \int f(\theta) d\theta = 1$ has been adopted. For each photon in the simulation, we re-generate the “observed” direction which may deviate θ from the “real” direction with probability $f(\theta)$.

We simulate 10000 observations with $N = 14$ photons each. These photons are assumed to come from an angle $\xi \leq 5^\circ$ around the Galactic center since all the 14 signal photons identified in [5] were from such a very compact region, where $\cos \xi = \cos \ell \cos b$ (for the Einasto DM density profile, just about 1/4 of the signal photons will be from $\xi \leq 5^\circ$, implying that there are many more signal photons from larger angles, which however may have been hidden behind the dense background). The average center of the photons is estimated to be

$$\ell_0 = \sum_{i=1}^N \ell_i / N, \quad b_0 = \sum_{i=1}^N b_i / N. \quad (3)$$

The distribution of the resulting (ℓ_0, b_0) is presented in the left panel of Fig. 2.

The offset of the morphology center compared with the Galactic center is simply $r = \sqrt{\ell_0^2 + b_0^2}$. We also investigate the asymmetric property of the photon map, through defining the elongation rate

$$\sigma_\ell / \sigma_b = \sqrt{\frac{1}{N} \sum_{i=1}^N (\ell_i - \ell_0)^2} / \sqrt{\frac{1}{N} \sum_{i=1}^N (b_i - b_0)^2}. \quad (4)$$

In the right panel of Fig. 2 we show the distribution of r and σ_ℓ / σ_b . Lines in this figure present the 1σ and 2σ contours. It is shown that an offset of about 1.5° revealed by the data is consistent with the canonical DM distribution within 2σ confidence level. Specifically the probability of $r > 1.5^\circ$ is about 2% (or 2.3σ), for the case $N = 14$. Our prediction will be directly tested by the ongoing and upcoming high energy observations. The results also show that a potential asymmetry between the longitude and latitude directions [5] may also appear due to the limited statistics.

With the increase of photon statistics, we would expect the deviation of the morphology center from the real center to decrease. The resulting distributions of the parameters for $N = 30, 50$ and 100 , still for 10000 simulations, are shown in Fig. 3. Given more and more photons we find that the fluctuation of the morphology center becomes smaller and smaller, as expected. The probability for a large offset of the morphology center is accordingly much smaller. For $N = 30$ we have $P(r > 1.5^\circ) = 0.02\%$. This probability decreases to 8×10^{-7} for $N = 50$, and becomes much smaller for $N = 100$. Obviously, the morphology will be more symmetric given more photons are detected.

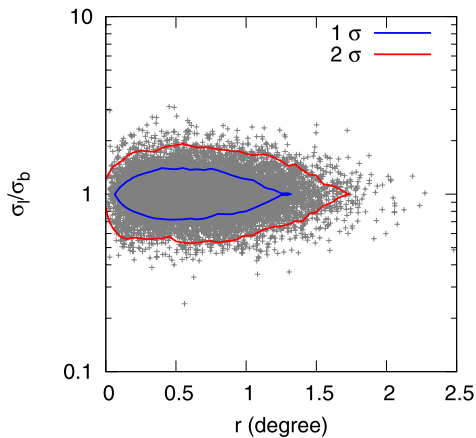


Fig. 2. Left: scattering plot of (ℓ_0, b_0) in the 10^4 simulations; right: scattering plot of offset angle r versus the elongation rate σ_ℓ / σ_b . (For interpretation of the colors in this figure, the reader is referred to the web version of this Letter.)

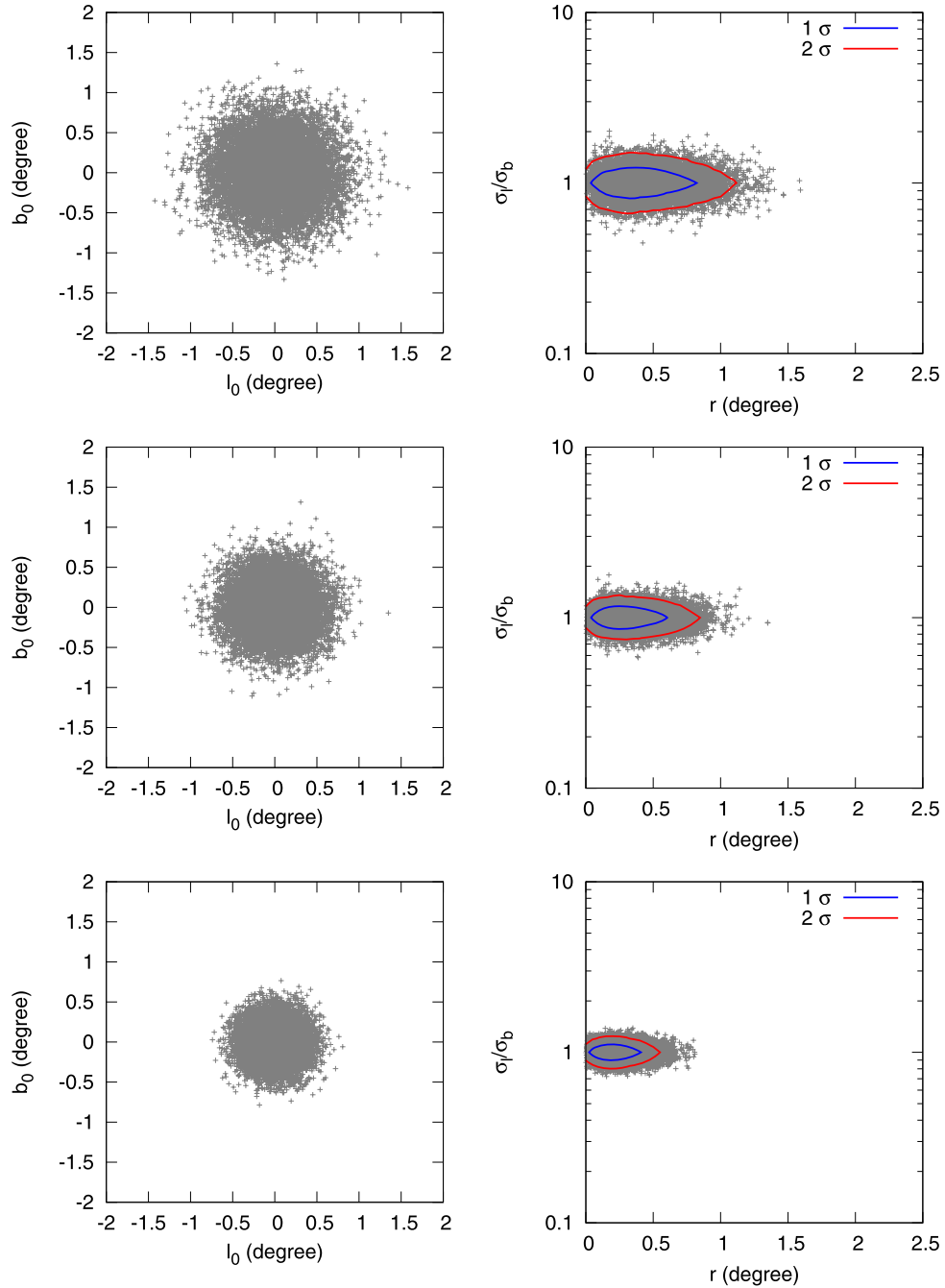


Fig. 3. Same as Fig. 2, but for $N = 30$ (top), $N = 50$ (middle) and $N = 100$ (bottom) respectively. (For interpretation of the colors in this figure, the reader is referred to the web version of this Letter.)

In summary we have shown that the spatial distribution of 130 GeV γ -ray line signal identified in [5] can be consistent with the DM annihilation model and the offset of the signal region from the Galactic center is likely caused by the limited statistics. The upcoming high energy resolution detectors such as DArk Matter Particle Explorer (DAMPE) and CALorimetric Electron Telescope (CALET)³ will be more powerful in identifying the line-like γ -ray signal (e.g., [12]). These two detectors however have an effective area smaller than Fermi-LAT, and the total photons detectable should also be fewer. We thus do not expect to get a perfect co-

incidence of the signal region with the expected DM distribution even in future observations. In this Letter the distribution of dark matter particles in the central Galaxy is assumed to be centered at $(\ell, b) = (0^\circ, 0^\circ)$. If it is not the case an offset larger than that predicted in our simulation is likely and the current spatial distribution of the signal photons might be better reproduced.

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³ <http://calet.phys.lsu.edu/>.

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References

- [1] T. Bringmann, X. Huang, A. Ibarra, S. Vogl, C. Weniger, arXiv:1203.1312.
- [2] C. Weniger, arXiv:1204.2797.
- [3] E. Tempel, A. Hektor, M. Raidal, arXiv:1205.1045.
- [4] A. Boyarsky, D. Malyshev, O. Ruchayskiy, arXiv:1205.4700.
- [5] M. Su, D.P. Finkbeiner, arXiv:1206.1616.
- [6] J.F. Navarro, C.S. Frenk, S.D.M. White, *Astrophysical Journal* 490 (1997) 493.
- [7] J. Einasto, *Trudy Astrofizicheskogo Instituta Alma-Ata* 5 (1965) 87.
- [8] E. Dudas, et al., arXiv:1205.1520;
J.M. Cline, arXiv:1205.2688;
- K.-Y. Choi, O. Seto, arXiv:1205.3276;
- B. Kyae, J.-C. Park, arXiv:1205.4151;
- H.M. Lee, M. Park, W.-I. Park, arXiv:1205.4675;
- A. Rajaraman, T.M.P. Tait, D. Whiteson, arXiv:1205.4723;
- B. Samir Acharya, et al., arXiv:1205.5789;
- X. Chu, et al., arXiv:1206.2279;
- D. Das, U. Ellwanger, P. Mitropoulos, arXiv:1206.2639;
- Z. Kang, et al., arXiv:1206.2863.
- [9] S. Profumo, T. Linden, arXiv:1204.6047.
- [10] F. Aharonian, D. Khangulyan, D. Malyshev, arXiv:1207.0458.
- [11] W. Buchmuller, M. Garny, arXiv:1206.7056;
T. Cohen, et al., arXiv:1207.0800.
- [12] Y. Li, Q. Yuan, arXiv:1206.2241.
- [13] J. Chang, et al., *Nature* 456 (2008) 362.
- [14] V.V. Mikhailov, et al., *Bulletin of the Russian Academy of Sciences: Physics* 75 (2011) 316.
- [15] L. Feng, Q. Yuan, Y.Z. Fan, arXiv:1206.4758.
- [16] M. Su, private communication, 2012.